NNSA Laboratory Directed Research & Development

Discovery and Innovation for National Security

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Ultra-low Field MRI: Seeing Vision in Action

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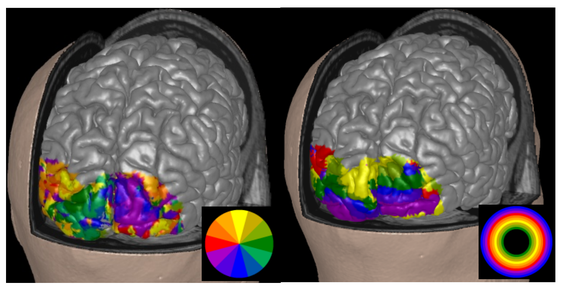
What is the challenge?

There is presently no technique that can image both the "when" and "where" of visual cognition. Magnetoencephalography (MEG) and electroencephalography (EEG) provide direct and high temporal measurements of neural activity that have been used to show differences in total processing time between tasks, such as when we recognize or fail to recognize objects. However, MEG and EEG have poor spatial resolution and cannot where in the brain this difference is originating. Conversely, studies in functional magnetic resonance imaging (fMRI) indicate spatial differences in activation patterns for processing different classes of objects. However, because fMRI has poor temporal resolution, we cannot know the temporal dynamics of how this difference is arising or which visual areas are processing when. This work will, *for the first time*, provide the tool to understand both the sequence and timing of events in a single non-invasive measurement. Knowing both is critical to improving our understanding of the brain.



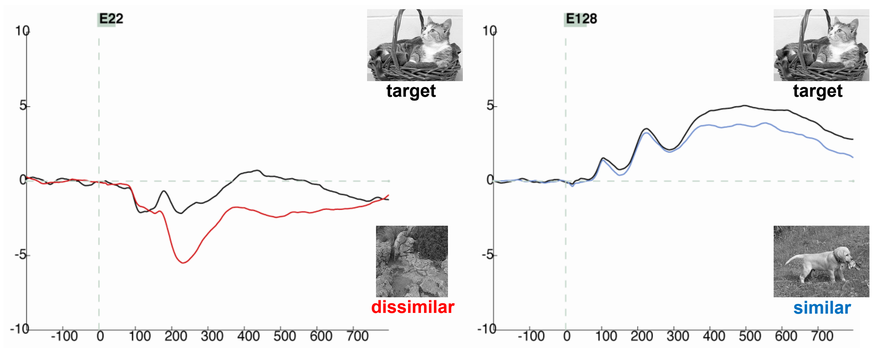
LEFT: fMRI retinotopic mapping (identifying which parts of the retina map to where in the brain) in response to a rotating (left) or expanding (right) checkerboard stimulus.

The fMRI signal typically takes seconds to evolve, too slow for the studies we propose. One can think a lot of different thoughts in such time! But we can use it to provide a functional map of visual cortex that we can use.

The speed of sight

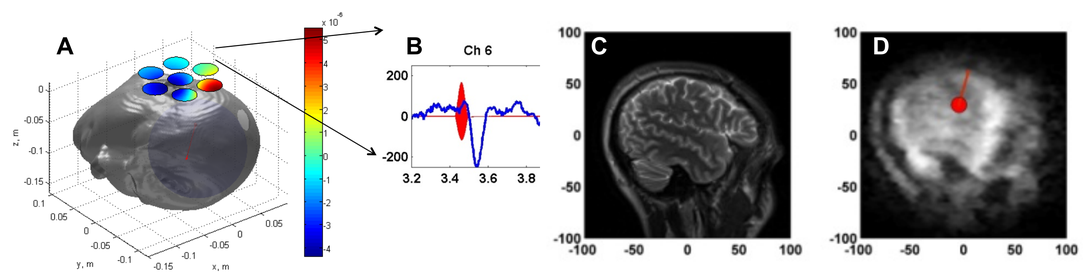
In this visual discrimination task, the subject pushes a button if they see images that correspond to their target (cats) vs. dissimilar images (e.g. nature) or similar images (e.g. dogs). We observe that the brain is very fast (too fast for feedback to occur) at telling apart dissimilar items. But it takes longer to discriminate the target from a similar item. Does the finer visual discrimination require feedback? The poor spatial resolution of EEG prevents direct observation of if /where feedback is occurring. Combined ULF MRI with MEG/EEG in a single measurement, can shed light on such processes.

Right: EEG measured event related potentials test a hypothesis of feed-forward vs. feed-back in visual processing. A 130 ms onset of differences is observed for telling apart the target from a dissimilar object. The onset of differences is longer, ~350 ms, when the object is similar.



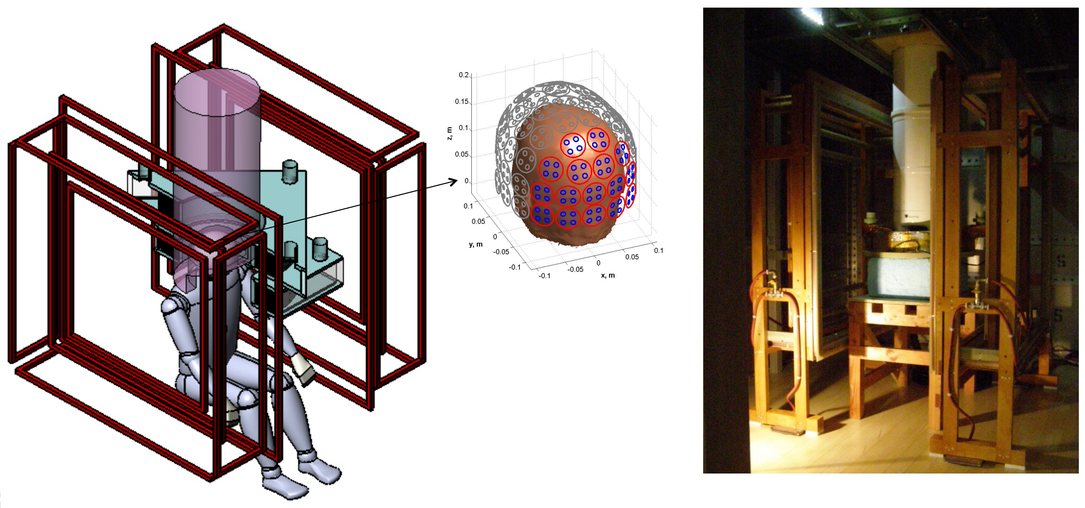
What have we learned so far?

We have learned that simultaneous ULF MRI and MEG can be combined for functional and anatomical imaging in a single device. Ours is a world's first demonstration!



(a) Sensor positions and map of recorded MEG fields during auditory stimulation. (b) Blue trace shows the recorded evoked auditory MEG waveform in one of the channels. Red trace indicate position of auditory stimulus. (c) MRI from a clinical scanner at 3T. (d) ULF MRI at 100 μT, acquired in the same experiment as the MEG. The earth's magnetic field is 50 μT. The red arrow shows where the MEG activity was co-registered to the ULF MRI.

To improve on the quality of both our MEG and ULF MRI , we need a dense sensor array and to increase the pre-polarization field to develop the best possible multi-modal imaging tool with optimal coverage of visual cortex. At the same time we our new instrumentation will allow us unprecedented flexibility to develop new imaging methods.



Schematic of the ULF MRI/MEG device. The helmet showing 64 MEG channels (blue circles) and 16 MRI channels in the visual cortex region is shown center. At far right is the assembled system in the commissioning phase.

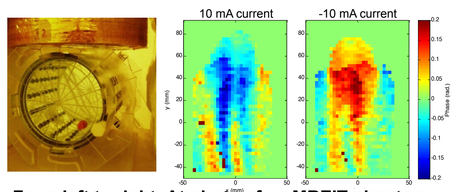
What is our innovation?

Magnetic resonance imaging or MRI is one of the most ubiquitous and powerful tools for non-invasive imaging of soft-tissue anatomy. fMRI is a form of MRI that measures changes in blood flow or oxygenation related to brain function, but these methods are slow (> 1sec) and somewhat indirect indicators of brain function. Because the MRI signal scales linearly with the applied magnetic field the technological trend has been towards higher magnetic fields (requiring larger magnets). Ideally one would combine MRI with MEG/EEG, however this is very difficult (in the case of EEG) if not impossible (in the case of MEG) because the signals and instruments are swamped by the high magnetic field of the MRI.

LANL now leads the world in ultra-low field (ULF) MRI, similar to conventional MRI, but using magnetic fields thousands of times smaller. Novel magnetic field pulsing combined with ultra-sensitive detection makes ours the only approach capable of combining the anatomical specificity of MRI with the high temporal resolution of MEG to *measure both the dynamics and origin of cognition*. The method may also provide new ways to image brain activity.

Can we directly image thought?

We are developing magnetic resonance electrical impedance (MREIT) based methods to measure brain structure . MREIT is a method where we can apply currents and measure the effect on the MRI. MREIT is a tool for detection of cancer, and brain pathology. But changes in impedance associate with neurons firing may also alter the image. The flexible pulse sequences and interesting regimes of tissue impedance < 10kHz in ULF MRI may enable direct measurement of neural activity. The currents that can be applied are typically ~ 1-10 mA, as opposed to the much smaller (μA) neural currents.

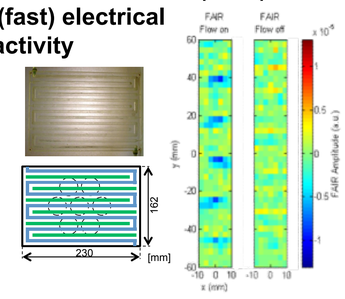


From left to right: At photo of an MREIT phantom (courtesy of EGI). Two ULF MRI phase images showing sensitivity to applied currents in two different polarities.

Having it all

We are developing new methods for fMRI based on blood flow at ULF. When combined with MEG we can provide critical validation between indirect (slow) hemodynamic and direct (fast) electrical measurements of neural activity

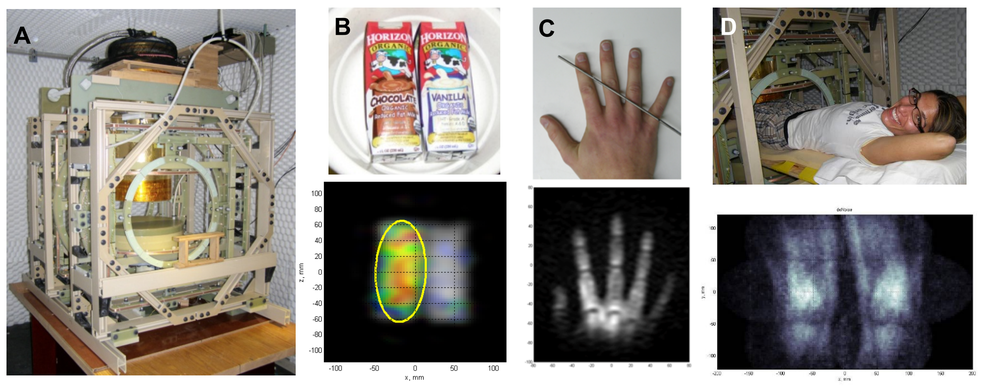
Left: A phantom (with flowing and static channels). Right: FAIR images with and without flow. Only flowing water is imaged.



Why is this important for our nation?

Advances in artificial intelligence, human-machine interface, enhancing cognitive capacity, memory, and information processing all depend on improving our understanding of the brain. Treatment of important medical conditions from depression to Alzheimer's disease may hinge on such progress. There is a growing recognition of the role that neuroscience will play in national security, from computers that think like people to improved training. At LANL we have a unique opportunity to advance such understanding of the brain.

- The ULF MRI capability advanced by this work has made significant impacts to research supported by the Department of Homeland Security in detection of liquid explosives.
- Advances in ULF MRI will also provide a path forward for low-cost portable MRI systems available for the battlefield, emergency room, and rural settings.
- Both fields of use for ULF MRI technology in security and medicine have been recently licensed.



A. An ULF MRI system (MagViz) built for the DHS was modeled on our first brain imaging device. B. Photo and image of foil-lined milk boxes. The threat hidden in the chocolate milk is clearly discriminated. We can also tell the difference between unadulterated chocolate milk and regular milk (as well as different makes of the same type of wine). C. Photo and image of the human hand. The hand was imaged with an aluminum rod in place. This is not possible with traditional MRI due to distortions cause by the high magnetic fields interacting with the conductor. D. ULF MRI images of the human knee obtained from MagViz. The subject was dressed in street clothes, including a magnetic zipper and her glasses, for this scan.

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